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## **Use of geographical information system-based hydrological modelling for development of a raised bog conservation and restoration programme**

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1        **Use of Geographical Information System-based Hydrological Modelling for Development of a**  
2                                **Raised Bog Conservation and Restoration Programme.**

3        **Abstract**

4        Peat-accumulating active raised bog (ARB) constitutes an Annex I priority habitat under the European  
5        Union's Habitats Directive (HD). Ecological monitoring of Irish special area of conservation (SAC) sites from  
6        the mid-1990s up to 2013 has shown that the network experienced ARB losses of 37% (730 ha) since the  
7        HD came into law. Obligations to restore ARB coverage, while conserving existing priority habitat, require  
8        a scientifically-defensible methodology to underpin long-term management. GIS-based investigative tools  
9        provided a basis for linking ecological and hydrological field data with high resolution topographic data.  
10       Application of semi-empirical hydrological metrics, reflecting climate, topographic conditions and  
11       surface/near surface hydrological processes, to uncut (high) bog indicated ARB typically develops on uncut  
12       peatlands with slopes of between 0.2% and 0.6%, depending on effective rainfall; in more localised  
13       focused-flow flushes ARB may occur on slopes exceeding 1%. Locating topographically suitable high bog  
14       areas, currently lacking ARB, permitted identification of degraded raised bog (DRB), i.e. zones capable of  
15       regenerating to ARB. Across the SAC network modelling suggested DRB coverage is 1555 ha, although  
16       not all may be restorable by tried-and-tested restoration technologies. Hydrological modelling has permitted  
17       identification of areas where restoration efforts may be focused for maximum benefit. On the other hand the  
18       approach has also highlighted the inability of restoration measures on high bog alone to meet the current  
19       shortfall in ARB and the requirement to consider additional approaches to restoration.

20       (230 words)

21       **Keywords**

22       Peatlands       Priority Habitat       Conservation Plans       Ecohydrology       Active Raised Bog       GIS  
23       Modelling       Habitats Directive       Restoration

24       **Research Highlights**

25       Irish raised bog SACs have experienced 37% loss in priority habitats since the 1990s  
26       Restoration obligations require scientifically-defensible modelling protocols  
27       GIS-based modelling provides a basis for identifying restorable areas  
28       Model outputs allow focusing of resources for long term restoration and management  
29       Results show a need for additional restoration techniques and hydrological research

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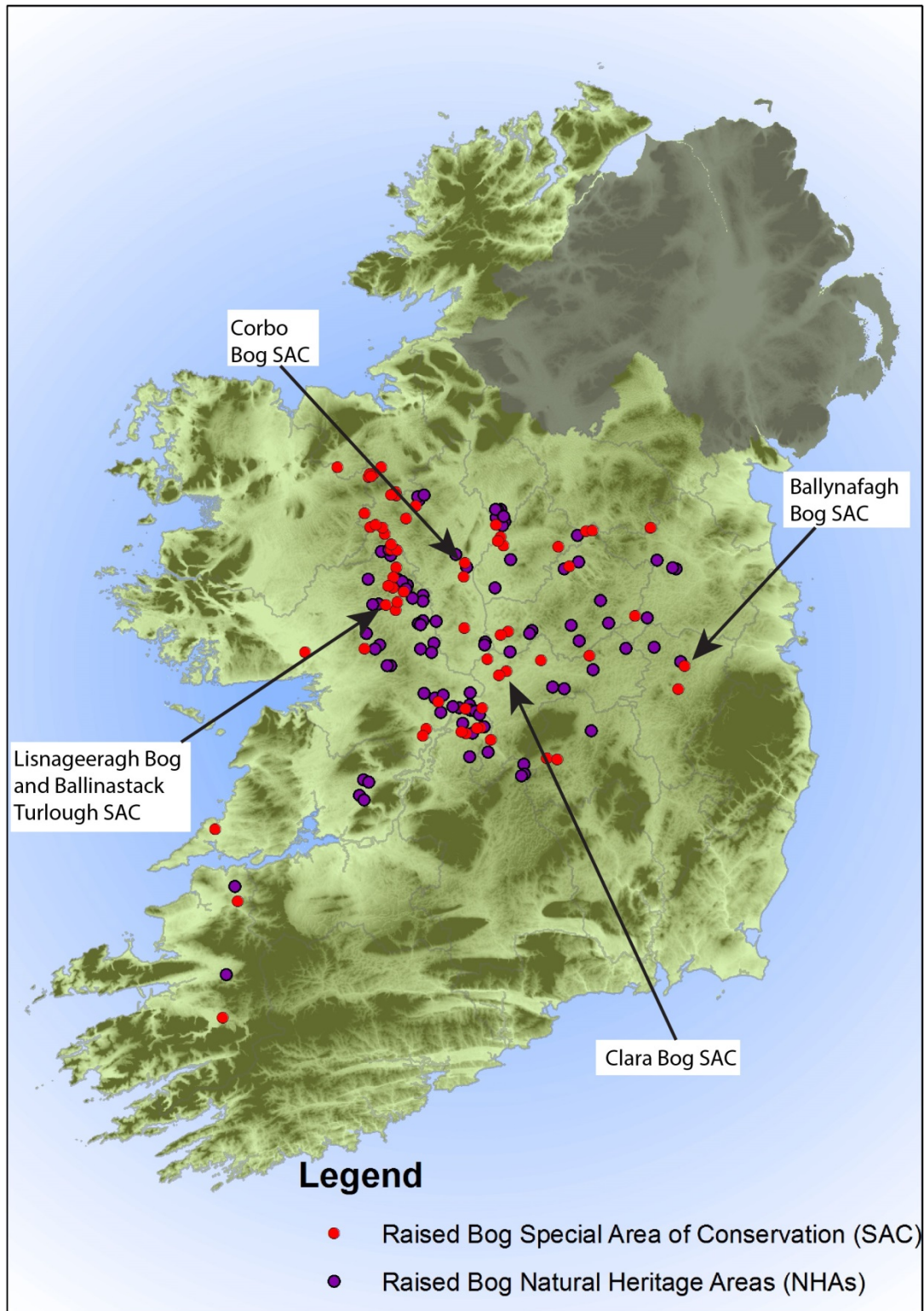
## 1 Introduction

2 Increasing recognition of the role played by peatlands in environmental regulation has led to changed  
3 perceptions of their wider importance (Evans et al., 2014). Potential benefits ranging from carbon  
4 sequestration to acting as reserves for biodiversity present a basis for their conservation (Wilson et al.,  
5 2013). However, the desire to conserve peatlands in Ireland often conflicts with traditional perceptions of  
6 their use. Across the Irish Midlands bogs have historically been viewed as areas to be reclaimed for fuel  
7 and additional land for agriculture and forestry (Mitchell and Ryan, 1997).

8 Raised bog reclamation rates have accelerated from the latter half of the 20<sup>th</sup> century onwards with the  
9 mechanisation of peat extraction for electricity generation and commercial horticulture compost (Clarke,  
10 2010). Thick sequences of peat, present in the largest Irish raised bogs, are particularly suitable to  
11 mechanised harvesting. As a consequence, all large bogs (>500 ha) in the eastern part of the Irish  
12 Midlands have now been drained and developed for production. Although larger bogs remain less  
13 damaged in the western part of the midlands (up to 880 ha), systematic drainage, associated with  
14 reclamation, continues to impact on their hydrology, as it does on smaller raised bog fragments across the  
15 whole country. Overall approximately 50,000 ha of the original raised bog coverage of 310,000 ha remains  
16 uncut (~16%) (NPWS, 2015). Of this site-specific studies suggest that the ecology of large areas of the  
17 remaining uncut (high) bog have been impacted by drainage (Schouten et al., 2002).

18 The negative impacts of drainage on Irish raised bog ecosystems have been recognised for some time (van  
19 der Schaff, 1999). Drains cutting across high bog, as well as those installed around bog margins, lower  
20 water tables in peat and hinder the maintenance of hydrological supporting conditions necessary for the  
21 survival of peat accumulating vegetation, such as *Sphagnum* sp. Approaching drains, impacts become  
22 particularly significant, with water tables often declining significantly below ground surface for prolonged  
23 periods (Kelly, 1993); these conditions prevent survival of peat-accumulating plant communities.

24 Losses of raised bog in Ireland reflect a wider trend across the European Union, which has witnessed  
25 dramatic decline in the habitat and peat-accumulating plant communities it can support. Concern about the  
26 rate of loss has prompted the European Union to classify peat-accumulating areas on raised bog, also  
27 known as Active Raised Bog (ARB), as an Annex I priority habitat under the EU Habitats Directive (HD)  
28 (European Commission Directive, 1992). More specifically the directive requires member states to  
29 implement measures aimed at conserving Annex I peatland habitats within national territories. In the  
30 Republic of Ireland (Ireland) this is achieved through the state's network of Special Areas of Conservation  
31 (SACs), which form part of a EU-wide Natura 2000 network of protected sites; a network of additional  
32 Natural Heritage Areas (NHAs) have a lesser degree of protection, while also contributing to the national  
33 raised bog resource (Figure 1).



**Figure 1:** Map of the distribution of raised bog Special Areas of Conservation (SACs) and Natural Heritage Areas (NHAs) across the Republic of Ireland. The figure highlights locations specifically mentioned in the text.

Monitoring of the distribution and health of Annex I habitat forms an integral element of the HD. In the case of Irish raised bog SACs, monitoring of peat-accumulating habitats is achieved through routine ecotope mapping, where plant communities, developing under particular hydrological conditions are recorded.

1 These ecotopes can be used to reflect the ecohydrological health of raised bogs (Kelly and Schouten,  
2 2002). (Table S-1 in the supplemental material accompanying this article summarises the conditions  
3 typically encountered in each ecotope and the criteria employed in mapping them.)

4 Routine mapping of ecotopes on most SACs, at five to six year intervals, has permitted changes in the  
5 extent of active raised bog within the SAC network to be monitored under Article 17 of the HD. Where  
6 monitoring has indicated declines in the health and/or extent of Annex I habitat, the HD obliges member  
7 states to implement measures to restore habitat to match coverage at a reference period. In Ireland the  
8 Irish National Parks and Wildlife Service uses as the date of implementation of the Habitats Directive at  
9 protected sites as the reference period, or when a site was declared protected, should it be later than this  
10 date. At the time of implementing the HD in Ireland, raised bogs were already considered in a degraded  
11 state, albeit with many areas capable of restoration to ARB, pending the implementation of tried-and-tested  
12 engineered measures, notably damming or infilling of high bog drains. The HD also requires that areas  
13 capable of regenerating to ARB at this time be restored. Consequently coverage needs to meet or exceed  
14 the area of ARB, along with impacted areas capable of supporting ARB with restoration measures, at the  
15 time when the HD came into force. Achieving these goals requires a scientifically defensible tool to identify  
16 of the causes of habitat degradation and determine appropriate restoration measures.

17 The causes of ARB loss can be manifold. In Ireland they are believed to relate primarily to changes in  
18 hydrological regime. As a result, restoring and maintaining hydrological conditions forms a fundamental  
19 building block contributing to the success of Irish raised bog conservation programmes. However,  
20 knowledge concerning the importance of critical hydrological elements on raised bog ecology is necessary  
21 if sustainable long term restoration and conservation is to be achieved.

22 Detailed studies at Clara Bog SAC (Clara) (Figure 1) in the 1990s revealed a close yet complex relationship  
23 between the distribution of ecotopes and surface /near surface hydrological processes (Kelly and  
24 Schouten, 2002). More specifically, findings at the site suggested a correspondence between topographic  
25 slopes and the occurrence of ARB, with slopes exceeding 0.3% generally proving incapable of supporting  
26 ARB, except in areas of focused flow, known as flushes.

27 Drainage can alter raised bog hydrology and its relationship with ecosystems (Ecohydrology) (van der  
28 Schaff, 2002). As in other geological media, drainage systems on high bog and/or in adjacent marginal  
29 areas can lower groundwater pressure. However, because of its highly compressible nature, the decline in  
30 water pressure (and associated buoyancy) in peat can lead it to subside under its own weight, with  
31 subsidence proving greatest immediately adjacent to drains (Hobbs, 1986). The differential rate of peat  
32 subsidence generally increases otherwise gentle slopes approaching bog drains. This affects how water  
33 behaves, with subsequent change in the bog's ecohydrological regime arising from a greater proportion of  
34 water running off in areas closer to drains, rather than ponding/infiltrating to maintain persistently high water  
35 tables required to support ARB.

Quantification of both the impacts of drainage on ARB coverage and on the topographic conditions necessary to support its restoration have proven challenging, given the difficulties in obtaining representative topographic data. Research completed at Clara in the 1990s relied on limited spot topographic measurements and water level data, collected on a temporally intermittent basis (Schouten et al., 2002). Since this time further development of remote sensing technologies, notably LIDAR, has permitted relatively inexpensive collection of higher resolution topographic data. Generation of these data, coupled with findings from more recent peatland hydrological investigations, have permitted a reappraisal of prevailing concepts concerning dominant hydrological processes influencing ARB occurrence. This in turn has led to the development of a refined conceptual model of Irish raised bog ecohydrology. This paper describes the approach adopted as part of the Irish National Parks and Wildlife Service's (NPWS) policy to develop a long term raised bog conservation and restoration programme, incorporating these developments. Work has integrated findings of existing research on Irish raised bog ecohydrology, with the results of detailed topographic datasets. Application of hydrological findings generated by the study of the Raised Bog SAC network has provided a basis around which further conservation and restoration measures may be developed.

## **Methodology**

### **A. Climatic Influences**

Identifying causes of habitat degradation can prove challenging due to the range of potential variables that may influence ecosystems. Nonetheless Mitsch and Gosselink (1993) note that water, and more specifically hydrological conditions, play a fundamental role in determining wetland ecosystem health. In the case of ombrotrophic systems, such as raised bogs, the role of rain proves fundamental in both helping maintain water levels and in the provision of low levels of nutrients (Hobbs, 1986). As a corollary to this point, it needs to be noted that changes in climatic conditions can result in alterations of total rainfall and rainfall frequency regimes, both of which influence raised bog distribution.

The Irish climate has proven particularly conducive to raised bog development (Bellamy, 1986). High levels of effective rainfall (rainfall-actual evapotranspiration), occurring throughout the year, help maintain high peatland water tables needed to support ARB. On the other hand, these requirements make the habitat sensitive to minor changes in climate. To assess the potential impact of climate change on hydrological supporting conditions, since the Habitats Directive came into force, a comparison of climatic data, available from 12 synoptic weather stations, run by the Irish Meteorological Service (Met Eireann), was undertaken. Comparison of total rainfall, effective rainfall (total rainfall – actual evapotranspiration (Misstea et al, 2009)) and frequency of rainfall (rain days) for the period from 1961-1990, with data collected in the period from 1981-2010, permitted evaluation of whether significant changes in climatic conditions had occurred over the more recent period. The analysis also provided a countrywide basis for assessing whether there had been significant spatial variations in critical climatic parameters responsible for ombrotrophic ecosystem health. Detailed analysis of ecotope hydroperiods (frequency that water table lies within a given distance of the ground surface) at four sites across the country, during a three-year period, revealed that conditions

1 differed little between ecotopes at all sites between October and March, whereas contrasts between  
2 ecotopes are particularly notable during the period from April to September; this is when the effects of  
3 evapotranspiration are more significant (van der Schaff, 1999). Based on these findings analyses of  
4 meteorological records focused on data collected in the latter summer period.

5 Analysis of data for the two 30-year periods involved comparison of median values of climatic data for  
6 meteorological stations, with differences considered statistically significant at the 5% level. This permitted  
7 assessment of whether climate had altered significantly on a countrywide basis. In the case of statistically  
8 significant differences, non-parametric analysis of variance (Kruskal-Wallis) of individual stations provided a  
9 means of assessing whether differences in the more recent data set were larger or smaller than the  
10 preceding period and thus whether changes in climatic conditions contributed to recent losses in ARB  
11 coverage. Plotting differences for stations on national maps, in turn provided an overview of how any  
12 variation may have occurred across the country.

13 B. Development of spatial model for assessing supporting conditions

14 Hydrological flow balance calculations completed by van der Schaff (1999) pointed to surface and near-  
15 surface processes as the dominant hydrological pathways for discharging effective rainfall from the Irish  
16 Midland Raised Bog research site at Clara. The semi empirical model developed, based on point  
17 topographic measurements from a 100 m x 100 m grid, underpinned investigations to assess whether  
18 surface hydrological processes could generate correspondence between topography and occurrence of  
19 peat accumulating ecotopes, i.e. flushes, areas of Central Ecotope and areas of Subcentral Ecotope. More  
20 specifically the modelling process involved relating suitable supporting topographic conditions, including  
21 surface shape, slope and drainage patterns to identify locations where these occurred, i.e. it assumed  
22 surface hydrological processes underpin the development and persistence of ARB.

23 The van der Schaff model (2002), based on limited topographic data, considered upstream flow path length  
24 (L) and local surface slope (s) as fundamental physical parameters underpinning the hydrological  
25 supporting conditions for ARB. A formula, based on the capacity of the upper more permeable layer of peat  
26 (acrotelm) to transmit water provided the basis to define a hydrological parameter, potential acrotelm  
27 capacity:

28 
$$PAC = \frac{L}{fs}$$

29 , where

30 PAC = Potential Acrotelm Capacity (km)

31 L = Upstream Flow Path Length (m)

32 s= Local surface slope (m km<sup>-1</sup>)

33 f = dimensionless flow path shape factor

34 Although based on hydrological processes, PAC proved difficult to apply with confidence, largely due to  
35 difficulties in defining a value of f; these arise because of the potential range of variation in flow path shape,



1 with  $f=1$  considered as a compromise in most cases. Following its use on Clara, application of the approach  
2 to a further six raised bog sites, all situated in the central part of the country, permitted thresholds for ARB  
3 development to be estimated, with reasonable correspondence obtained between ARB and a PAC value  
4 greater than 50.

5 The versatility of the PAC approach was further examined in the current research, which required a method  
6 for identifying hydrological conditions suited to ARB occurrence across the suite of raised bogs extending  
7 over the habitat's full range in Ireland. Under these circumstances climatic conditions prevailing across the  
8 country proved more variable than at the sites upon which the method was piloted. Moreover, in its original  
9 application limited topographic data only permitted the approach to determine PAC at given points, often  
10 based on interpolation between widely spaced topographic measurements. Since this time the availability  
11 of high resolution LIDAR topographic data for all SACs has expanded the scope of possible hydrological  
12 analyses; this has permitted further application of PAC and the generation of maps reflecting areas  
13 considered to have suitable hydrological supporting conditions for ARB occurrence. In total, the approach  
14 permitted maps of PAC for all 53 Raised Bog SACs to be generated and the utility of the model to be  
15 scrutinised with greater confidence.

16 Evaluation of the correspondence between ecotope occurrence and PAC for the SACs suggested some  
17 shortcomings in the model. Firstly, there were areas where ARB occurred that the model often did not  
18 adequately identify. This proved particularly notable in areas of convergent flow paths, where the extent of  
19 ARB was often underestimated.

20 Secondly, it was observed that the PAC model generated some over-estimation of areas of ARB on several  
21 sites, particularly approaching the eastern end of the range of raised bog occurrence; this indicated that the  
22 threshold value, obtained from the PAC method, typically associated with bog margins was too low.

23 Thirdly, there was a notable under-estimation of coverage of areas of potential restoration of active raised  
24 bog in locations with higher effective rainfall. This highlighted bias arising in using a PAC formula,  
25 developed for a limited number of sites in the Midlands, where contrasts in climatic conditions proved less  
26 than across the entire range for the habitat, as recognised by the original researchers (van der Schaff and  
27 Streefkerk, 2002).

28 To address discrepancies in the PAC method, the following modifications to the topographic modelling  
29 process were applied.

- 30 1. Assessment of PAC performance in areas of convergent flow suggested that flow path length could  
31 be replaced by upstream contributing catchment area in a manner more consistent with widely  
32 employed topographic parameters, such as the topographic index developed by Beven and Kirkby  
33 (1979). In order to account for accumulation along more than one flow path leading to a point, an  
34 alternative parameter that accounted for contributing catchment area was proposed. This aimed to  
35 provide an improved measure of the upstream catchment area contributing to discharge at a certain



point, particularly when flow path convergence occurs. This, when coupled with topographic gradient, yielded the flow accumulation capacity (FAC).

$$FAC = \frac{\sqrt{A}}{s}$$

FAC = Flow Accumulation Capacity (km)

A = Upstream contributing catchment area (flow accumulation) (m<sup>2</sup>)

s = Local surface slope (m km<sup>-1</sup>)

High resolution topographic data permitted spatial application of the approach over finely discretised areas. Through a process of trial and error, cell sizes of 20 m x 20 m were found to minimise confounding effects of microtopography on slope. Application to LIDAR datasets for each SAC thus permitted FAC to consistently account for the flow pattern/shape and identify those areas considered topographically suitable for ARB occurrence.

2. To account for variation in climatic conditions across the country, model modification was necessary. Plotting FAC against effective rainfall (generated through interpolation between 25 Met Eireann synoptic monitoring stations) suggested a log-linear relationship that permitted threshold values for ARB to be estimated on a countrywide basis through comparison with ARB occurrence (Figure 2).

3. The resulting best -fit log-linear regression equation permitted suitability for ARB development across the range for raised bog occurrence to be estimated while incorporating climatic variation. To permit conditions between sites to be examined using common metrics, comparison was made relative to conditions at Clara, which lies approximately in the centre of the range of Irish midland raised bogs and also has areas unimpacted by high bog drainage on its western side. This gave rise to the modified flow accumulation capacity (MFAC) as follows:

$$MFAC = FAC \cdot K$$

where K is an empirical climatic correction factor (km<sup>-1</sup>).

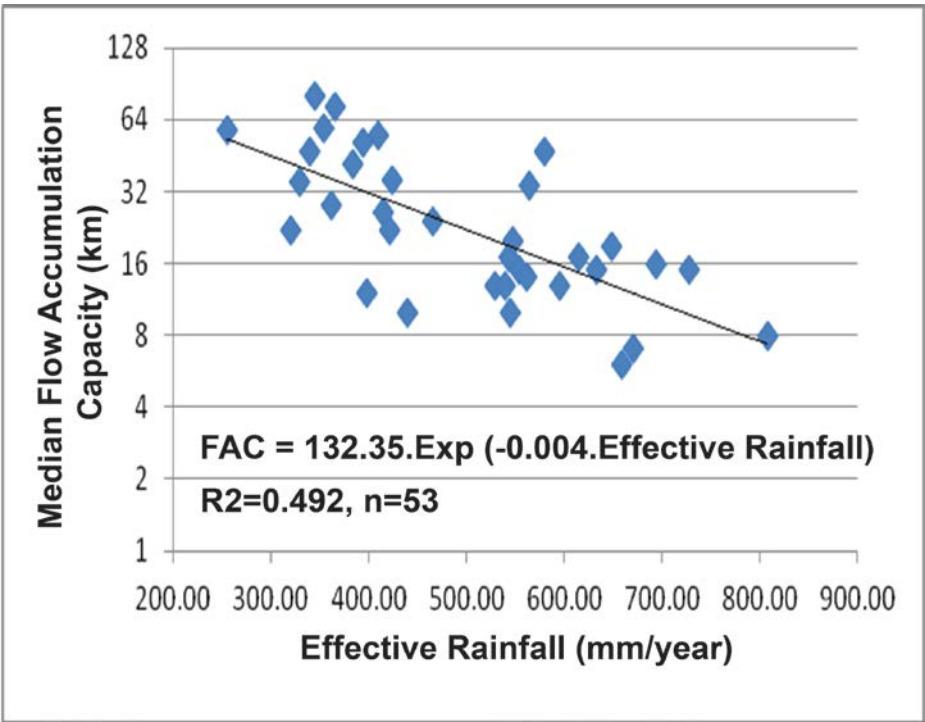
Evaluation of the effectiveness of MFAC and PAC was achieved by determining the area capable of supporting ARB using both metrics and comparing with mapped ARB coverage. This was achieved not only by comparing global coverage on a site-by-site basis, but also by visually comparing simulated ARB occurrence (as reflected by MFAC>30 and PAC>50) with results of the most recent ecotope mapping.

To remove the potential influence of high bog drains, both methods were applied on a subset of four sites spanning the distribution range of Irish raised bogs where high bog drains were considered to have minimal impact on site ecohydrology in the most recent ecotope surveys, completed within three years of the 2012 LiDAR surveys (See Figure 1 for their locations). Two metrics were employed to facilitate comparison of model efficiencies. The ratio of observed (mapped) ARB coverage (ARB<sub>mapped</sub>) to that simulated by the model (ARB<sub>simulated</sub>) permitted the model's capacity to reflect observed ARB distribution; a value closer to

unity reflects a better model fit. A second metric provided an indication of the extent to which the approaches over-predicted the area of active raised bog. This was achieved by determining the proportion of simulated ARB, which does not correspond to mapped ARB, to total simulated ARB coverage. This latter parameter may be expressed mathematically as follows:

Excess Simulated ARB=1-(ARB<sub>mapped</sub>/ARB<sub>modelled</sub>)

In this case a value closer to zero reflects a better model fit.



**Figure 2:** Plot of Median Threshold Flow Accumulation Capacity (FAC) for Active Raised Bog development with effective rainfall for Irish Raised Bog SAC sites. Increases in effective rainfall permit ARB to occur in areas with steeper slopes and/or supported by smaller catchments.

### Model Application

The requirement to restore damaged Annex I habitat under the HD can place significant demands on human and financial resources. Moreover, implementation of the HD to the Irish Raised Bog SAC network requires restoration not only of areas containing ARB, but also damaged areas capable of supporting ARB following the application of restoration measures, otherwise known as degraded raised bog (DRB), at the time of declaration. At the same time, it needs to be acknowledged that in some cases damage may be irreparable and tried-and-tested engineered interventions to restore supporting conditions may prove ineffective.

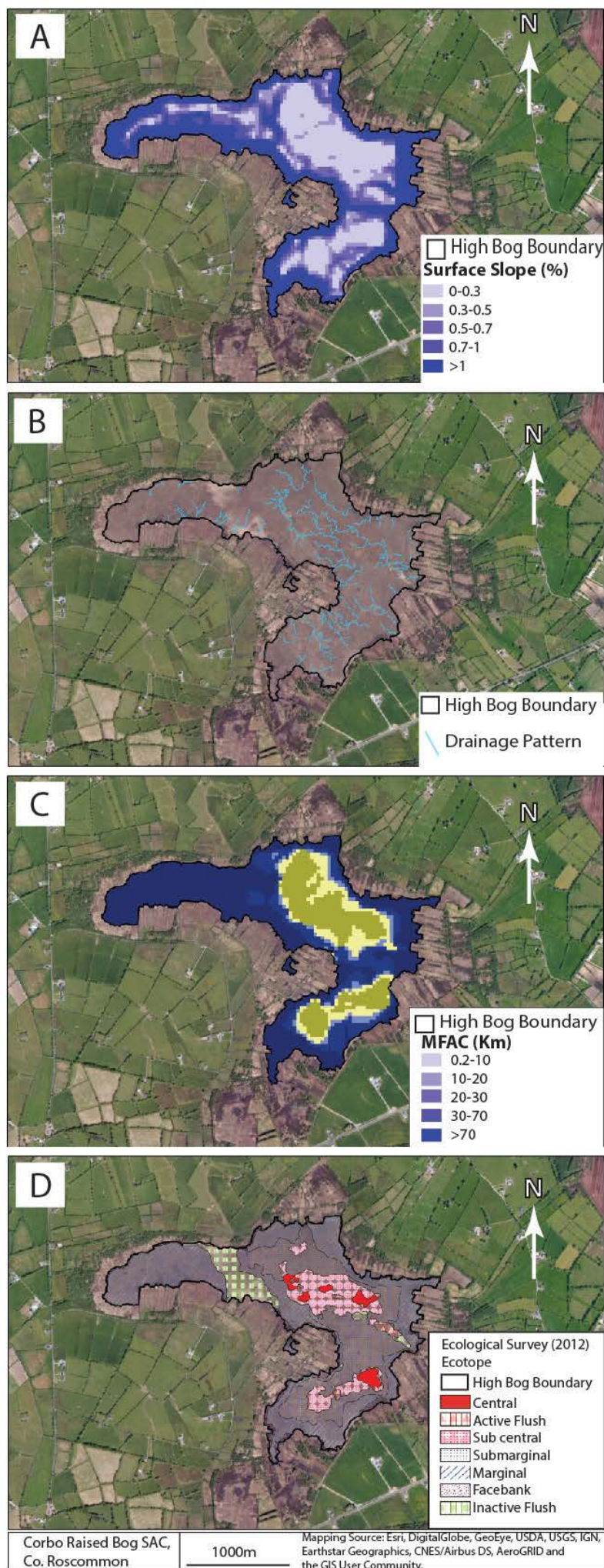
Detailed studies completed on parts of Clara, where the confounding impacts of high bog drainage proved minimal , notably on Clara Bog West, demonstrated that conditions in marginal drainage can dramatically

1 alter the capacity of high bog to support ARB though topographic changes linked to subsidence (van der  
2 Schaff, 2002). Furthermore, investigations at Raheenmore Bog SAC, examining the impact of bunding  
3 along the edges of uncut peatland, have shown that in areas impacted by drainage-related subsidence,  
4 changes to topography are largely irreversible (Gill and Johnston, 1999) and rewetting cannot restore bog  
5 topography and slopes to permit re-establishment of peat accumulating conditions on high bog. As a  
6 corollary to this point there is a risk that restoration may prove futile in areas of where suitable topographic  
7 conditions are absent in the immediate surroundings.

8 MFAC and PAC analysis, using LIDAR data and the ARCGIS® Hydro tool, for all raised bog SACs  
9 permitted identification of topographically suitable areas for restoration, i.e. definition of DRB on a site-  
10 specific basis. Figure 3 provides a graphical summary of the development of a spatially distributed MFAC  
11 map for Corbo Bog SAC; a comparable approach was employed for the PAC map. The figure reflects the  
12 successive stages of model development, building on LIDAR topographic data to develop slope maps.  
13 These in turn can be used to identify flow paths, using the ARCGIS® Hydro tool to define a catchment for  
14 any point on the bogs surface. Processing these data thus allows both maps of PAC and MFAC for sites  
15 with LIDAR data to be developed.

16 DRB identification for each site was considered as those areas where modelling predicted ARB, yet ARB  
17 was not observed. This in turn permitted identification of topographically suitable areas where restoration  
18 efforts would most likely lead to re-establishment of suitable hydrological supporting conditions required for  
19 ARB development. In other words the approach provided a means of establishing scientifically- defensible  
20 site-specific restoration targets across the raised bog SAC network.

21 Completion of modelling at all sites also provided a basis for assessing the change in extent of ARB and  
22 DRB across the SAC network since a reference period, when the Habitats Directive came into force.  
23 Comparison of differences in ARB coverage on a site-by-site basis allows areas of ARB loss through time  
24 to be defined. On the other hand definition of DRB at the start of this reference period proved more  
25 problematic. The absence of sufficient high quality topographic data has meant that DRB could not be  
26 defined through numerical modelling before 2012, when LIDAR surveys for all sites were completed.  
27 Consequently to determine DRB in the mid-1990s reliance was placed on using model outputs from most  
28 recent topographic surveys in conjunction with the results of earlier ecotope monitoring and maps of the  
29 bog margins. (Despite HD requirements, cutting has continued on many SACs so that high bog boundaries  
30 have often altered significantly in the intervening period.)

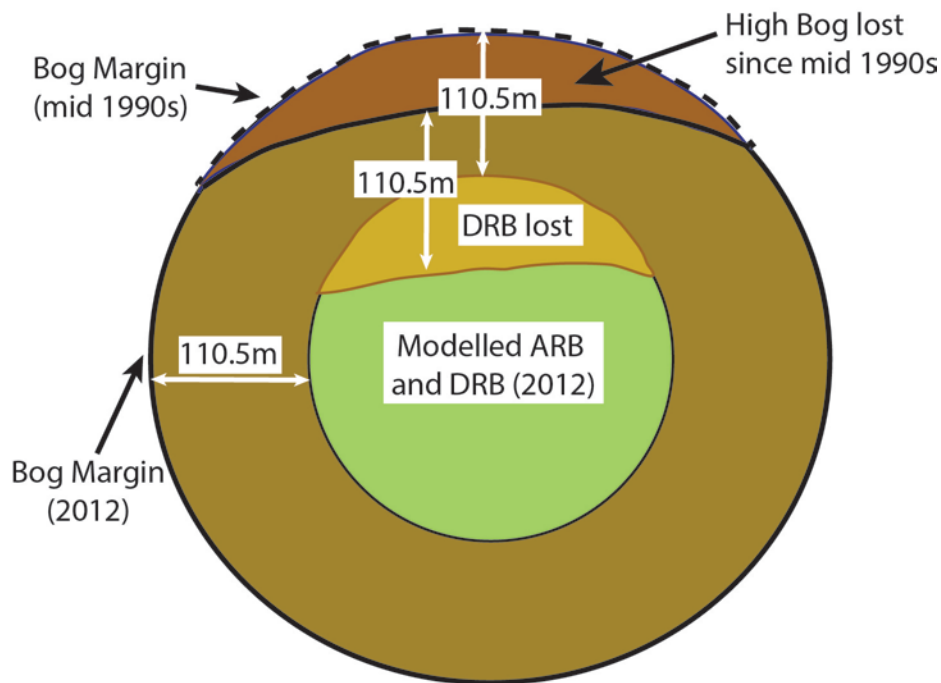




1 Fig. 3. Summary of Development of MFAC Map for Corbo Bog SAC. (A) Slope gener-ation from site-  
2 specific LIDAR Data, (B) Flow path generation from ARCGIS© HydroTool, (C) MFAC mapping of high bog,  
3 based on slope and catchments determinedfrom flow paths; PAC mapping employs a similar approach but  
4 using flow pathlength rather than catchment area. (D) 2012 Ecotope Map of Corbo Bog SAC.

5 A statistical survey of model outputs for all sites involved determining the median distance from the high  
6 bog margin to the closest area of either ARB or DRB. Extending this distance from bog margins determined  
7 from mid-1990s aerial imagery thus provided an estimate of aggregate ARB & DRB for each site at the time  
8 (Figure 4). Subtracting the ARB, determined from 1990s ecotope maps, thus permitted estimation of DRB  
9 coverage for the time. Although imprecise, the approach was considered adequate for determining DRB  
10 when the network of raised bog protected sites is considered as a whole, i.e. it acts as a global solution.  
11 Comparison with the most recent simulations for each site thus allowed the loss of DRB to be estimated  
12 over the intervening period.

13 Determination of losses of ARB and DRB, following this approach, permitted national restoration targets to  
14 be established. Most critically, it provided a means of assessing where ARB can re-establish in the SAC  
15 network, and how much compensatory habitat may be obtained through restoration measures from  
16 topographically suitable sites. Overall modelling identified areas where restoration activity would generate  
17 greatest benefit. On the other hand, application of site specific hydrological modelling outputs permitted  
18 identification areas and sites where restoration measures may have little to no benefit.

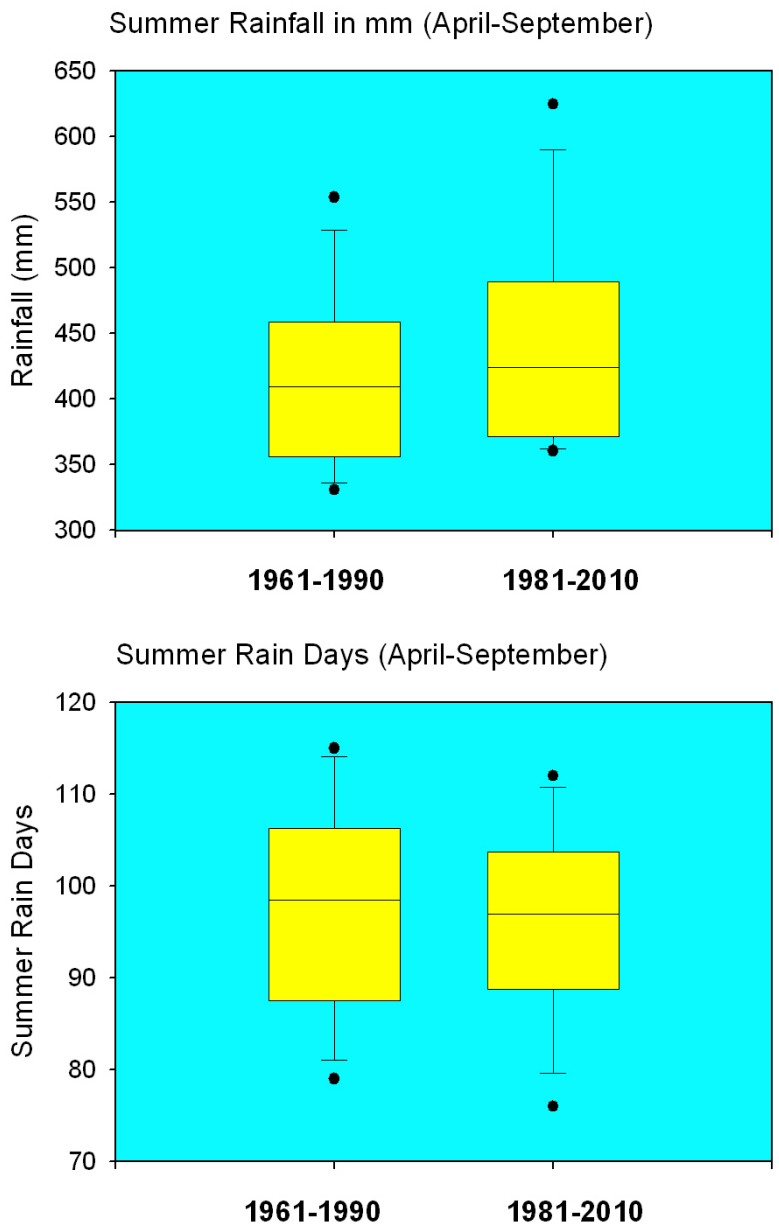


19  
20 **Figure 3:** Schematic Illustration of estimation of loss of DRB on Irish Raised Bogs in the SAC network  
21 since the 1990s. Over the network, a median distance of 110.5m from the bog margin to first DRB  
22 occurrence, based on 2012 data, was extended in to uncut bog from the margin measured in the mid-  
23 1990s to estimate the occurrence of DRB at this time. The loss in DRB was calculated as the difference  
24 between this area and that estimated by applying the same distance to the current margin.

1   **Results and Discussion:**

2   Evaluation of nationwide changes in those climatic parameters considered important for supporting peat  
3   accumulating vegetation (total rainfall, effective rainfall and rainfall frequency) across Met Eireann’s  
4   hydrometric network between 1981 and 2010, compared to 1961-1990, failed to display any significant  
5   differences for rainfall or effective rainfall, including during the summer period for the country as a whole  
6   (Figure 5). Similarly no significant difference in the number of rain days was encountered across the  
7   network between both periods.

8



9  
10 **Figure 5:** Box and whisker plots comparing (a) rainfall and (b) rain days for the summer period (April-  
11 September) at Met Eireann (Irish Meteorological Service) synoptic weather stations for 1961-1990 and  
12 1981-2010.

1

2



Site_Name	Most Recent Ecotope Map*	Total Mapped ARB (ha)	Total PAC-modelled ARB (ha)	Observed ARB, simulated by PAC (ha)	% ARB identified by PAC	Excess Simulated ARB (PAC)	Total MFAC-modelled ARB (ha)	Observed ARB, simulated by MFAC (ha)	% ARB identified by MFAC	Excess Simulated ARB (MFAC)
Ballynafagh Bog SAC	2011	6.48	20.40	6.09	94	0.68	7.84	4.25	66	0.17
Clara Bog SAC (west)	2009	79.92	143.31	69.47	87	0.44	109.08	59.71	75	0.27
Corbo Bog SAC	2012	15.51	33.22	14.86	96	0.53	29.93	14.64	94	0.48
Lisnageeragh Bog and Ballinastack Turlough SAC	2012	29.61	65.27	19.21	65	0.55	57.61	19.86	67	0.49

\*All LIDAR surveys completed in 2012

1 **Table 1:** Comparison of PAC and MFAC outputs for simulating ARB occurrence in four Irish raised bog SAC sites spanning the habitat's distribution range.

2

1 Table 1 summarises model metrics for the four test sites spanning the range of raised bog occurrence for  
2 both PAC and MFAC outputs. Simulations of ARB occurrence using both methods, presented for Corbo  
3 Bog (Figure 3), revealed both methods broadly reproduced the distribution of ARB observed. This  
4 compares with outputs for both methods over large parts of the western section of Clara Bog (Figure 6).  
5 Results show that both approaches manage to simulate the majority of observed ARB distribution, with  
6 PAC covering more of the observed occurrence at three of the four pilot sites. However, this metric alone is  
7 misleading as PAC outputs also encompasses larger areas of high bog that do not host ARB. This is  
8 reflected in the contrast in excess simulated ARB generated with both approaches, which is consistently  
9 lower for MFAC than for PAC outputs, thus reflecting better model fit.

10 The capacity of the model to reproduce ARB distribution across the test sites suggests that model  
11 assumptions concerning the role of surface and near-surface processes as the dominant mechanisms  
12 contributing to ARB hydrological supporting conditions are valid. Overall, comparison between model  
13 metrics for the test sites suggests that MFAC more effectively reflects occurrence and that adaptations  
14 made to the original model to reflect catchment area were appropriate.

15 Although no climatic correction was applied to MFAC for Clara, as all other sites are compared to Clara,  
16 application to other sites across the country has allowed climatic variation to be incorporated into MFAC to  
17 assist in improving the model fit. At the same time, differences between the methods are often slight,  
18 further corroborating the common model assumption that very gentle topographic slopes underpin  
19 hydrological supporting conditions for the Central and Sub-central ecotopes that contribute to ARB  
20 coverage; these slopes range between 0.2% and 0.6% at the eastern and western ends of the habitat's  
21 range respectively. By contrast, focused flow in flushes can help to maintain peat accumulating vegetation  
22 on slopes exceeding 1%. The overall capacity of the MFAC approach to better reproduce ARB coverage  
23 further highlights the greater importance of catchment size rather than flow path length in supporting its  
24 occurrence.

25 Available ecotope maps, along with the use of the MFAC to calculate total ARB and DRB resources across  
26 the SAC network, suggested that in 1994 the network contained 1940 ha of ARB and a further 1004 ha of  
27 DRB. By contrast, in 2012 ARB coverage had reduced to 1210 ha. At the same time MFAC modelling  
28 indicated that DRB coverage had increased to 1555 ha, partially reflecting the loss of ARB at many sites,  
29 even though conditions for restoration remained topographically suitable. Table 2a and Table 2b  
30 summarise findings for the network on a site by site basis.

31 Restoration of hydrological supporting conditions in areas of DRB across Ireland currently relies on tried-  
32 and-tested methods, notably the blocking of high bog drains. Activities carried out on Lisnageeragh Bog  
33 and Ballinastack Turlough SAC (Lisnageeragh) have demonstrated that this approach can result in  
34 significant reversals in the loss of ARB over relatively short periods (Figure 7). Monitoring data for the bog  
35 reveal that between 1994 and 2012 the area of ARB had increased from 13 ha to 29.6 ha, while modelling  
36 suggests that DRB declined from 54.9 ha to 37.8 ha over the same period, largely reflecting the success of  
37 the restoration programmes. Most of this reversal occurred over the eight years between 2004 and 2012.

- 1 (An aggregate decline of 0.5 ha over this period largely reflects the impact of on-going marginal peat cutting
- 2 in the intervening period.)

Site_Name	Most Recent Ecotope Map*	Total ARB (ha)	Total potential ARB area identified by MFAC >30 (ha)	Mapped Area ARB identified by MFAC (ha)	DRB Area (MFAC Simulated ARB - identified ARB (ha))
All Saints Bog and Esker SAC	2011	39.78	52.60	22.26	30.34
Ardagullion Bog SAC	1999	20.98	12.88	9.05	3.83
Ardgraique Bog SAC	2003	10.28	3.96	0.62	3.34
Ballyduff-Clonfinane Bog SAC	2011	17.74	33.04	8.00	25.04
Ballynafagh Bog SAC	2011	6.48	7.84	4.25	3.59
Ballynamona Bog and Corkip Lough SAC	2000	25.12	9.84	8.76	1.08
Barroughter Bog SAC	2005	2.38	2.36	0.44	1.92
Bellanagare Bog SAC	2013	49.59	130.08	24.91	105.17
Brown Bog SAC	2012	10.77	2.36	2.17	0.19
Callow Bog SAC	2012	11.30	56.24	8.16	48.09
Camderry Bog SAC	2012	6.18	25.18	3.98	21.19
Carn Park Bog SAC	2013	3.15	20.93	2.28	18.66
Carrowbehy-Caher Bog SAC	2012	69.87	72.20	36.97	35.24
Carrownagappul Bog SAC	2012	28.07	64.55	14.40	50.15
Clara Bog SAC	2009	111.51	163.01	77.56	85.45
Cloonchambers Bog SAC	2012	7.66	47.01	4.98	42.03
Clooneen Bog SAC	1999	11.17	9.84	2.19	7.65
Cloonmoylan Bog SAC	2005	52.30	171.89	38.88	133.01
Cloonshanville Bog SAC	2012	20.12	58.00	12.89	45.11
Coolrain Bog SAC	1999	31.36	13.36	13.18	0.18
Corbo Bog SAC	2012	15.51	29.93	14.64	15.29
Corliskea-Trien-Cloonfelliv Bog SAC	2013	69.14	75.77	21.10	54.67
Crosswood Bog SAC	2012	4.64	9.32	1.37	7.95
Curraghleanagh Bog SAC	2012	9.85	33.66	5.35	28.31
Derrinea Bog SAC	2012	17.04	24.74	15.07	9.67
Drumalough Bog SAC	2003	5.08	47.43	1.12	46.31
Ferbane Bog SAC	2012	32.64	17.64	12.25	5.39
Flughany Bog SAC	2012	11.41	16.81	3.74	13.06
Garriskil Bog SAC	2011	50.87	50.77	28.69	22.08

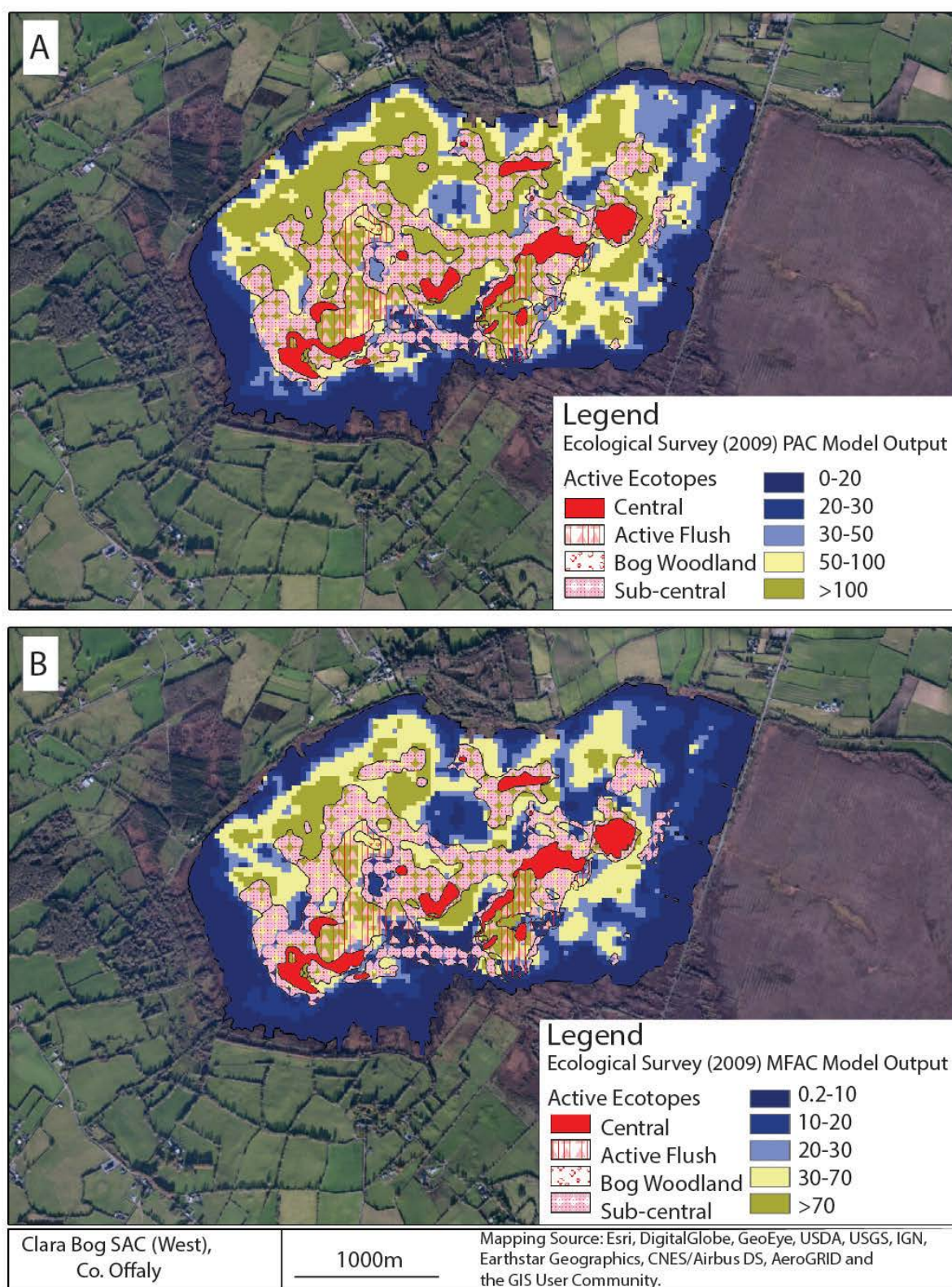
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2 **Table 2a:** Summary of results of MFAC modelling of Irish Raised Bog SACs (All Saints to Garriskil Bog).  
3 Simulations broadly reproduces the distribution of peat accumulating active raised bog (ARB) indicated by  
4 ecotope mapping, although areas are often over estimated, particularly in areas of high bog drainage.

Site_Name	Most Recent Ecotope Map*	Total ARB (ha)	Total potential ARB area identified by MFAC >30 (ha)	Mapped Area ARB identified by MFAC (ha)	DRB Area (MFAC Simulated ARB - identified ARB (ha))
Kilcarren-Firville Bog SAC	2011	28.66	111.34	25.27	86.07
Killyconny Bog (Cloghbally) SAC	2011	3.91	12.04	2.53	9.51
Kilsallagh Bog SAC	2012	11.53	15.73	3.85	11.87
Knockacoller Bog SAC	2012	4.79	29.64	4.74	24.90
Lisnageeragh Bog and Ballinastack Turlough SAC	2012	29.61	57.61	19.86	37.76
Lough Corrib SAC	2012	39.86	95.46	36.52	58.94
Lough Forbes Complex SAC	2011	8.89	63.33	4.75	58.58
Lough Lurgen Bog-Glenamaddy Turlough SAC	2004 (W) / 1994 (E)	16.30	60.98	7.85	53.13
Lough Ree SAC	2003	5.93	47.69	3.04	44.65
Moanveanlagh Bog SAC	2012	4.59	15.60	0.93	14.67
Moneybeg and Clareisland Bogs SAC	2015	5.29	20.76	3.92	16.84
Mongan Bog SAC	2011	48.31	20.44	16.79	3.65
Monivea Bog SAC	2012	7.04	32.32	6.55	25.77
Mouds Bog SAC	1999	94.94	38.84	31.45	7.39
Mount Hevey Bog SAC	1999/2000	64.52	30.52	19.85	10.67
Moyclare Bog SAC	2012	21.70	28.36	20.03	8.33
Raheenmore Bog SAC	2011	52.32	48.32	36.87	11.45
Redwood Bog SAC	2012	12.11	40.28	8.35	31.93
River Moy SAC	1999-2012	51.80	195.12	42.94	152.18
Shankill West Bog SAC	2012	13.31	26.43	12.09	14.34
Sharavogue Bog SAC	2011	25.78	6.88	6.23	0.65
Sheheree (Ardagh) Bog SAC	2012	4.06	3.41	2.63	0.79
Tullaghanrock Bog SAC	1999	11.00	10.88	7.01	3.87
Tullaheer Lough and Bog SAC	1999	6.78	4.35	1.60	2.75

1

2 **Table 2b:** Summary of results of PAC and MFAC modelling of Irish Raised Bog SACs (Kilcarren-Firville to  
3 Tullaheer Lough and Bog). Mapping using both techniques broadly reproduces the distribution of peat  
4 accumulating active raised bog (ARB) indicated by ecotope mapping, although MFAC produces a better fit  
5 in the majority of cases.



1

2 Fig. 6. Comparison of (A) PAC outputs and (B) MFAC outputs for the western part of Clara  
3 Bog SAC. Areas with MFAC >30 provide a better overall fit to the observed ecotopes while  
4 areas with PAC > 50 provide a greater overestimation of ARB coverage in the eastern part

1 of the site. Both models over estimate coverage on the northwestern and southcentral parts  
2 of the SAC, due to significant vertical losses of water through the more permeable  
3 substrates that immediately underlie the peat in these areas. Neither model accounts for this  
4 process. North is at the top of each panel.

5 Despite the success of restoration measures at Lisnageeragh Bog, it is noteworthy that not  
6 all modelled DRB has been restored. Comparable situations have been noted at other sites  
7 and point to shortcomings in the model. This in part highlights the limited capacity of drain  
8 blockage to fully restore ARB. However, elsewhere ARB is absent in topographically suitable  
9 areas where high bog drainage has little to no impact. Although observations from sites such  
10 as Corbo suggested that surface and near-surface processes dominated the hydrological  
11 regime, this may not apply at other sites, or indeed over particular parts of a site. This lack of  
12 correspondence may occur where a significant proportion of effective rainfall discharges  
13 through peat to depth, particularly during prolonged dry periods. Although work at Clara has  
14 suggested site-wide annual discharge to depth to be less than 50 mm/year (van der Schaff,  
15 1999), the heterogeneous substrate conditions observed can give rise to locally elevated  
16 infiltration rates, even where topographically suitable conditions for ARB development occur.  
17 This is particularly evident on the northern side of Clara Bog in Figure 6, where both PAC  
18 and MFAC predict ARB occurrence, yet ecotope mapping shows it to be absent; coring in  
19 this area shows peat to be directly underlain by permeable esker sand and gravel, rather  
20 than less permeable lacustrine clays/marls or over-compacted silty glacial tills encountered  
21 elsewhere.

22 In a similar vein investigations of peat substrate completed at other sites suggest that  
23 permeable substrates, although underlying limited areas of bog, can occur in the geologically  
24 heterogeneous conditions routinely encountered across Ireland. The inability of either the  
25 MFAC or PAC models to incorporate this process, in part helps explain inexact  
26 correspondence between modelled and observed ecotope occurrence. In this respect the  
27 hydrological model employed provides a basis for identifying areas where the impact of  
28 subsurface hydrogeological processes on raised bog ecohydrology may require further  
29 investigation.

30 Quantification of the impacts of hydrological process on raised bog ecohydrology through  
31 distributed hydrological modelling thus provides not only a means of better understanding  
32 hydrological processes but also a fundamental basis for establishing management targets  
33 and appropriate resource allocation. The hydrological models employed in this study  
34 provided a means of not only identifying those areas suited to restoration measures because  
35 of topographic conditions, but also potentially highlighting areas where deeper  
36 hydrogeological processes could affect restoration efforts. Viewed in another way, use of the



- 1 tool provides a means of identifying areas where restoration measures are unlikely to
- 2 generate increases in ARB coverage; this in turn permits resources to be diverted and
- 3 targeted to areas where impacts of measures may prove more beneficial.

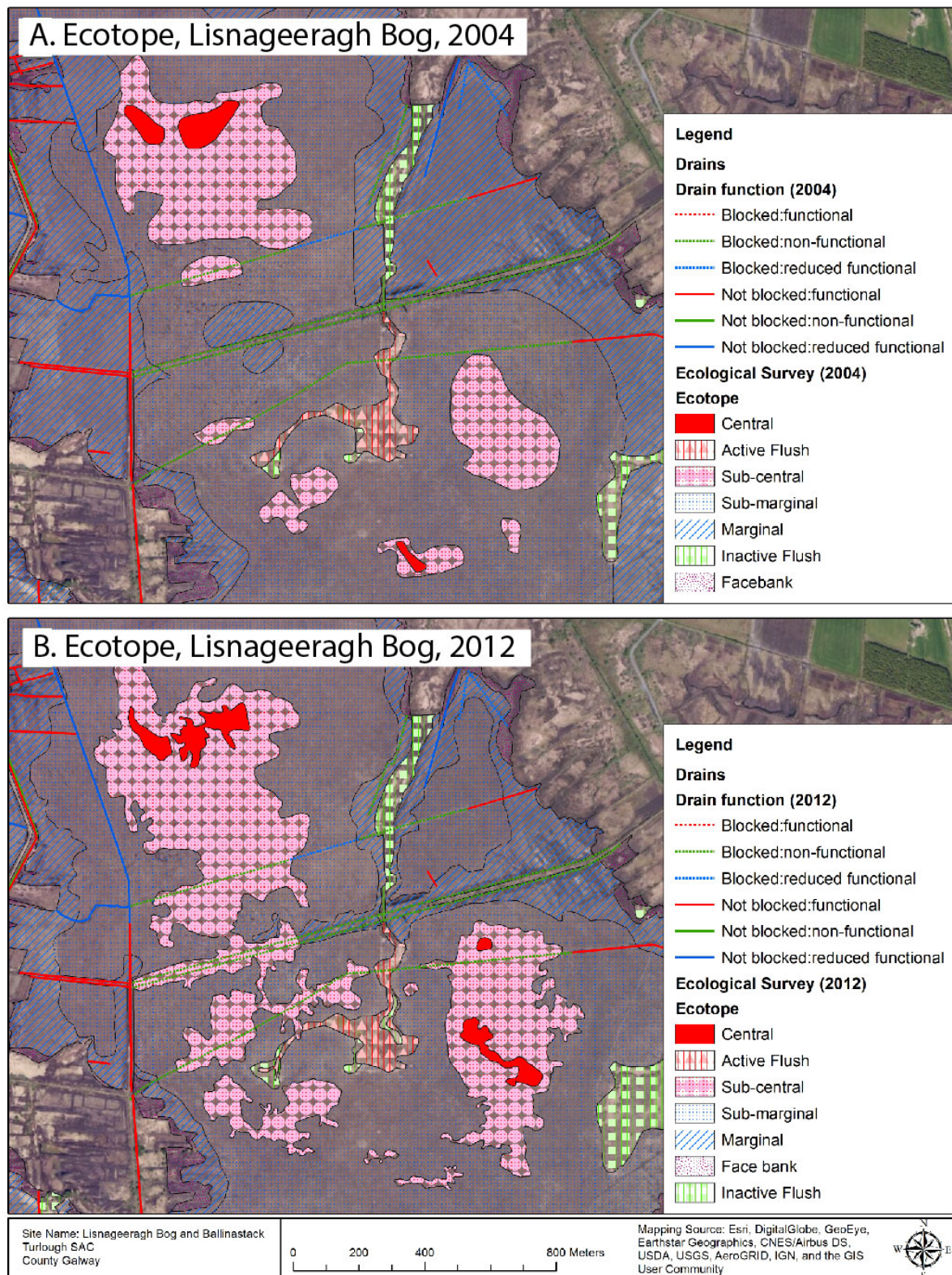


Fig. 7. Impact of drain blockage restoration measures at Lisnageeragh Bog (, part of Lisnageeragh and Ballinastack Turlough SAC). Drain blockage undertaken in 2004, across the central part of the site, aimed to increase the area of ARB. By 2012, areas of Subcentral and Central Ecotopes (in pink and red) had increased significantly. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

## Perspectives

Hydrological modelling through a GIS interface has succeeded in broadly reproducing ARB and DRB distribution at many Irish Raised Bog SAC sites. This provides a hydrological basis for development of long term conservation management plans and restoration targets for the Irish Raised Bog SAC network. Using the MFAC model for identification of areas capable of supporting ARB provides a useful basis for assigning scarce resources for maximum benefit. Conversely application of the model to sites of questionable value provides a means of assessing whether restoration through conventional tried-and-tested techniques would prove effective, or whether resources could be better allocated elsewhere.

In a related vein, the approach adopted can act as a means of examining whether other hydrological and hydrogeological processes, not considered to date by the model, may prove significant in influencing ARB distribution. Under these circumstances, application of the model, as part of a wider suite of investigative tools, provides a means for establishing whether other hydrological and/or hydrogeological processes, apart from those affecting surface and near surface, are contributing to ARB loss. Once again, hydrological modelling can assist in determining whether conventional restoration approaches may prove adequate, or whether additional measures addressing a wider range of pressures may be required. In cases where substrate groundwater regimes play a significant role in ecohydrological water balances, hydrological modelling displays considerable scope for integration with hydrogeological modelling tools, e.g. through identification of zones with contrasting recharge rates.

In all cases it needs to be stressed that confidence in the quality of outputs generated depends fundamentally on that of supporting datasets and that additional site-specific information will help further inform and strengthen the resilience of conservation and management plans. At the same time the inexact, and in some cases poor, correspondence between model outputs and observed ARB distribution highlights the need for further field-based research into Irish raised bog hydrology and hydrogeology to better tackle the causes of habitat degradation and to develop suitable restoration measures.

Finally, model results suggest that a national level ARB losses, incurred since 1994, cannot be compensated for using high bog restoration measures alone. This generates a need to consider alternative means of restoration, particularly on areas where high bog has already been cut (cutover). Botanical observations in these areas have shown them to be capable of regenerating to support peat accumulating ombrotrophic plant communities, comparable to those encountered on ARB, albeit over longer time frames. Research is currently underway to adapt the MFAC tool to identify those areas of cutover, where demonstrated restoration technologies, such as drain blockage and marginal bunding may be best applied. Preliminary results to date suggest good correspondence between vegetation and hydrological conditions, underscoring the further potential of hydrological modelling as a management tool for wetland conservation and restoration.

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